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**LITERATURE REVIEW OF LOW IMPACT
DEVELOPMENT FOR STORMWATER CONTROL**

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14. ABSTRACT The literature review provides information on current low impact development (LID) technologies available to treat metals and nutrients in stormwater runoff. The information in the literature review will be used to develop the Decision Support System, which is a guidance document for Navy personnel to select and design the most appropriate LID for industrial areas (see NESDI Project 493, "Stormwater Management Decision Support System for Using Low Impact Development Best Management Practices in Industrial Areas").					
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EXECUTIVE SUMMARY

This literature review is part of the effort for the NESDI research project Low Impact Development for Stormwater Control. The research project team is being led by NAVFAC EXWC and is supported by the Low Impact Development Center, Inc. The goal of this project is to establish protocols and a Decision Support System (DSS) that can be used to identify and select appropriate low-impact development (LID) strategies and technologies that eliminate and/or treat stormwater discharges from Navy industrial facilities. The primary focus is to address non-point source stormwater pollution that is contaminated from operations at industrial areas.

The major pollutants of concern in stormwater generated at Navy industrial facilities are metal contaminants, such as zinc (Zn), lead (Pb), and copper (Cu). Other pollutants, such as nutrients, in one or more forms of nitrogen (N) or phosphorus (P) are also of concern, depending upon the activities taking place and the concerns of the watershed where the facility is located. Eliminating or substantially reducing these pollutant loads are the regulatory focus of many stormwater permits in estuary or coastal areas where installations are located. The volume of stormwater that is generated from naval installations, as well as the resultant pollutant load, is also of increasing concern. This is because of the significant discharge fees for impervious areas that are being charged by municipalities and states to fund their compliance programs. LID strategies and technologies that can reduce pollutant loads and the volume of runoff, or discharge of stormwater, will be critical to compliance strategies and to reduce operational costs at installations.

The initial key findings of the LID literature review can be summarized as follows:

1. A significant amount of literature and studies exist on the treatment of metals in stormwater. This research has been sponsored by national research organizations such as, but not limited to, the US Environmental Protection Agency, the National Academy of Sciences Transportation Research Board, and the Water Environment Research Foundation. In addition, there have been privately funded studies by industries, large-scale private industrial property owners, and municipalities that have regulatory requirements to reduce metals pollution in stormwater. There are also recently initiated studies that are being conducted by the Washington State Department of Ecology. By knowing how metals can be treated, the user can select the appropriate LID for its site.
2. Metal and nutrient loadings can be reduced to some extent by pollution prevention and other operations management practices, but unavoidable releases need to be treated using structural Best Management Practices (BMPs) or LIDs. These releases are best dealt with using small, distributed BMPs rather than larger end-of-pipe practices. These practices must be tailored to address the particular pollutant loads encountered at naval industrial sites, and to reduce pollutant concentrations to meet regulatory requirements.
3. From laboratory experiments, there is a substantial understanding of the unit processes that are involved in the treatment and reduction of metals in stormwater. The significant gap in knowledge is how treatment systems perform in the field. By understanding the unit processes, the appropriate LID technology can be selected to capture the targeted

metal pollutant. Little information exists on the effects of field variables such as loading rates and volume, temperature, climate, pH, sediments, organics, and maintenance cycles on systems in the field.

4. The amount of research and guidance on stormwater treatment at recycling and industrial facilities is very limited. Only a handful of efforts that have been conducted or are underway study the specific operations at Navy or other DoD activities. Knowledge based on the characterization and sources (e.g., fences, operations, materials, etc.) is also very limited. The need is high to implement LID in industrial areas and monitor them for cost and maintenance information.

Several promising LID technologies or vendor BMP products can reduce metal pollutant and nutrient loads. The key will be to develop experimental designs in the laboratory and field that demonstrate the ability of the approaches to reduce loads to below representative permit limits and that the approaches meet the end user operational needs. The findings from this literature review will be used in the DSS.

ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of Highway and Transportation Officials
Al^{3+}	Aluminum Ion
ANAD	Anniston Army Depot
BMP	Best Management Practice
CEC	Cation Exchange Capacity
-COOH	Carboxyl Functional Groups
Cu	Copper
Cu^+	Monovalent Copper
Cu^{2+}	Divalent Copper
CWA	Clean Water Act
DoD	Department of Defense
DOM	Dissolved Organic Matter
DRMO	Defense Reutilization and Marking Office
DSS	Decision Support System
EISA	Energy Independence and Security Act of 2007
EMC	Event Mean Concentration
EO	Executive Order
EXWC	Engineering and Expeditionary Warfare Center
f_d	Dissolved Fraction
Fe^{3+}	Ferric Iron Ion
FY	Fiscal Year
GAC	Granular Activated Carbon
H_2PO_4^- and HPO_4^{2-}	Phosphate
IWS	Internal Water Storage
K_d	Partition Coefficient
LID	Low Impact Development
Mn^{2+}	Manganese Ion
MSGP	Multi-Sector General Permit
N	Nitrogen
N_2	Nitrogen Gas
NASNI	Naval Air Station North Island
NAVFAC ESC	Naval Facilities Engineering Service Center
NAVSTA	Naval Station, San Diego
NBC	Naval Base Coronado
NBK	Naval Base Kitsap
NBSD	Naval Base San Diego
NESDI	Navy Environmental Sustainability Development to Integration Program
NH_3	Ammonia Gas
NH_4^+	Ammonium
N_2O	Nitrous Oxide
NO_2^-	Nitrite
NO_3^-	Nitrate

NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRRC	Navy Regional Recycling Center
OH ⁻	Hydroxide Ion
-OH	Hydroxyl Functional Group
OM	Organic Matter
P	Phosphorus
PAHs	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PCBs	Polychlorinated Biphenyls
PGIS	Pollution-Generating Impervious Surface
PGPS	Pollution-Generating Previous Surfaces
SALs	Stormwater Action Levels
SCMs	Stormwater Control Measures
SON	Soluble Organic Nitrogen
SWMMWW	Stormwater Management Manual for Western Washington
SWMP	Stormwater Management Plan
SWPPP	Storm Water Pollution Prevention Plan
TMDLs	Total Maximum Daily Loads
TN	Total Nitrogen
TP	Total Phosphorus
UFC	Unified Facility Criteria
USEPA	United States Environmental Protection Agency
VDEQ	Virginia Department of Environmental Quality
VPDES	Virginia Pollutant Discharge Elimination System
VSMP	Virginia Stormwater Management Program
WDRs	Waste Discharge Requirements
WERF	Water Environment Research Foundation
WLA	Waste Load Allocations
WRIA	Water Resource Inventory Area
WTR	Water Treatment Residual
Zn	Zinc

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1.0 INTRODUCTION

Eliminating or substantially reducing pollutant loads are the regulatory focus of many stormwater permits in estuary or coastal areas where installations are located. The volume of stormwater that is generated from naval installations, as well as the resultant pollutant load, is also of increasing concern. This is because of the significant discharge fees for impervious areas that are being charged by municipalities and states to fund their compliance programs. Strategies and technologies that can reduce pollutant loads and the volume of runoff, or discharge of stormwater, will be critical to compliance strategies and to reduce operational costs at installations. Described below are some of the key physical settings and stormwater regulatory requirements that must be met at naval installations.

1.1 Description of Focal Sites

Three focal sites have been selected for this project that represent a range of climatic conditions so the strategies and BMPs can be developed to be as “universal” as possible. These sites also represent typical regulatory requirements that may be encountered in the region in which they are located. The project team will work with personnel at the installations to insure that the systems are viable and meet end user requirements during the development of the DSS. The selected installations are Naval Base Kitsap, Naval Base San Diego, and Naval Station Norfolk. The studies may also include operations at nearby installations or activities that are directly or indirectly involved with these facilities and facility managers.

1.1.1 Naval Base Kitsap, Bangor, Washington

The Naval Base Kitsap is located on the western side of the Kitsap Peninsula, across Puget Sound from Seattle. It borders Hood Canal to the west and is situated just north of Silverdale in Washington State. The base was created in 2004 by merging the former Naval Station Bremerton with the Naval Submarine Base Bangor. The mission of the base is to serve as the host command for the Navy’s fleet throughout West Puget Sound and to provide base operating services, including support to submarines, aircraft carriers, and surface ships having their homeports at Bremerton and Bangor.

Naval Base Kitsap is the third largest Navy base in the U.S. and the largest naval organization in Navy Region Northwest. It is also one of Washington State’s largest industrial installations. It features a dry dock, the Navy’s largest fuel depot, and a nuclear shipyard that support the base’s ship building and maintenance activities. It also includes the Strategic Weapons Facility Pacific which provides maintenance and spare parts, including nuclear warhead storage carried by nuclear submarines.

1.1.2 Naval Base San Diego, San Diego, California

The Naval Base San Diego is located in the eastern edge of San Diego Bay, southwest of San Diego, California. It is the largest base of the U.S. Navy on the west coast and is the principal homeport of the Pacific Fleet. The base covers a total area of approximately 1,300 acres - 300 of which is over water. The base is homeport to a large number of ships and provides logistical

support including repair and dry-docking facilities. It comes under the command structure of the U.S. Navy, Commander, Navy Region Southwest.

The Naval Base San Diego (NBSD) complex is comprised of four Navy installations: the Naval Base San Diego (NAVSTA); the Mission Gorge Recreational Facility; the Broadway Complex; and the Naval Medical Center, San Diego. NAVSTA will be the focus in this report, as it is the facility primarily engaged in ship maintenance and related activities that result in stormwater discharge of an industrial nature; the remaining facilities provide other support services and are located in and around San Diego. The mission of NAVSTA is to provide appropriate logistical support for the operating forces of the U.S. Navy and for dependent activities. It occupies 1,049 acres of land and water and supports waterfront operations, ship berthing and maintenance, training, and logistics functions. Operational facilities include piers, quay walls, small craft berthing facilities, fueling facilities, armories, a dry dock, and waterfront operations buildings.

1.1.3 Naval Station Norfolk, Norfolk, Virginia

The Naval Station Norfolk is situated in an area collectively called “Hampton Roads” in southeastern Virginia. Located on a peninsula known as Sewell’s Point in the City of Norfolk, the base occupies approximately 3,400 acres of land. The peninsula forms the southern border of the mouth of the James River as it flows into the Chesapeake Bay. Naval Station Norfolk is the largest naval complex in the U.S., supporting 75 ships and 134 aircraft alongside 14 piers and 11 aircraft hangers. It provides facilities and services to enable mission accomplishment and operational readiness of the U.S. Atlantic fleet. Apart from the naval port services, which see more than 3,100 ships move annually through the base’s port, it also conducts significant air operations that see more than 100,000 flight operations annually.

The Norfolk Naval Shipyard, which is part of the Naval Station, is located on the southern branch of the Elizabeth River in Portsmouth, Virginia. Encompassing approximately 800 acres, it is the largest and most multifaceted industrial facility that belongs to the U.S. Navy. The shipyard specializes in repairing, overhauling, and modernizing ships and submarines. Additionally, the yard performs manufacturing, research, development, and test work, including providing services and materials to various other activities as required.

1.2 Relevant Statutes, Policies, Guidance, and Regulations

The following is an overview of the key driving policies and regulations that will influence the DSS. Low impact development (LID) has become an increasingly important planning and design tool for Navy facilities nationwide as a means of complying with various stormwater requirements and resource protection goals. Several important pieces of federal legislation, Executive Orders, Secretary of Defense and Secretary of the Navy policies exist that promote or require the integration of LID technologies. Depending on the locality in which the Navy facilities operate, various state and local requirements may also be applicable. The following sections outline the federal statutes, regulations, and policies that are relevant to the planning and implantation of how low impact development technologies can be used for industrial activities on Navy property.

1.2.1 Federal Legislation and Policy

Several executive orders, guidance documents, and regulatory requirements at the federal level must be addressed when considering the use of LID at industrial facilities. These are often very complex and interrelated. The following is a brief summary of the programs and their potential impacts.

1.2.1.1 Energy Independence and Security Act (EISA) of 2007, Section 438

The EISA is a federal law enacted by Congress in December 2007 that, in Section 438, establishes strict stormwater runoff requirements for federal development and redevelopment projects. It requires federal projects with a footprint over 5,000 square feet to employ “site planning, design, construction, and maintenance strategies for the property to maintain or restore, to the maximum extent technically feasible, the pre-development hydrology of the property with regard to the temperature, rate, volume, and duration of flow.”

1.2.1.2 Executive Order 13423 (2007) Strengthening Federal Environmental, Energy, and Transportation Management

EO 13423 was signed on January 24, 2007 and was codified into law by the 2009 Omnibus Appropriations Act. It requires federal agencies to lead by example in advancing the nation’s energy security and environmental performance. Among other things, EO 13423 requires federal agencies to reduce water intensity (gallons per square foot) by 2% each year through FY 2015 for a total of 16% based on water consumption in FY 2007. It also requires federal agencies to ensure that new construction and major renovations implement the *Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings* (last updated 12/1/2008). Under Principle III, Protect and Conserve Water, the *Guiding Principles* contains the following language regarding stormwater management: “Employ design and construction strategies that reduce storm water runoff and discharges of polluted water off-site. Per EISA Section 438, to the maximum extent technically feasible, maintain or restore the predevelopment hydrology of the site with regard to temperature, rate, volume, and duration of flow using site planning, design, construction, and maintenance strategies.”

1.2.1.3 Executive Order 13514 (2009) Federal Leadership in Environmental, Energy, Economic Performance

EO 13514 (2009) was signed on October 5, 2009, in order to enhance the sustainability goals and requirements established in EO 13423. It also enhanced the implementation of EISA Section 438 on stormwater management by requiring the issuance of guidance on its implementation. Both the USEPA’s *Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the EISA* and the Navy’s *Unified Facility Criteria (UFC) 3-210-10 Low Impact Development*, dated 15 November 2010, provide additional guidance on how to apply the EISA’s requirements (USEPA, 2009; DoD, 2010).

1.2.1.4 Office of the Under Secretary of Defense EISA Section 438 Implementation Memorandum

Dated January 19, 2010, the Office of the Under Secretary of Defense EISA Section 438 Implementation Memorandum states that the DoD shall implement EISA Section 438 and the

USEPA Technical Guidance using LID techniques (Navy, 2007). The overall design objective for each project is set to maintain predevelopment hydrology and prevent any net increase in stormwater runoff. The DoD defines “predevelopment hydrology” as the pre-project hydrologic conditions of temperature, rate, volume, and duration of stormwater flow from the project site.

1.2.2 Federal, DoD, and Navy Guidance Documents

Guidance documents, Engineering Bulletins, Uniform Facilities Criteria, and Industrial Sector Storm Water Pollution Prevention Plan (SWPPP) fact sheets and guidance must be addressed in the design process, operations, and reporting. The following is a summary of the key documents that will be considered.

1.2.2.1 Environmental Protection Agency’s (USEPA) Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the EISA (2009)

Released in December 2009, the USEPA’s Technical Guidance was developed to assist federal agencies to determine how to implement stricter stormwater runoff requirements in federally funded development and redevelopment projects where impervious area increased by 5,000 square feet or more. The guidance focuses generally on retaining rainfall on-site through infiltration, evaporation/transpiration, and re-use to the same extent as occurred prior to development. It also provides two options for meeting the performance objective of preserving or restoring the hydrology of a site: retaining the 95th percentile rainfall event (i.e., managing rainfall on-site for storm events whose precipitation total is less than or equal to 95% of all storm events over a given period of record), or site-specific hydrologic analysis (i.e., using site-specific analysis to determine predevelopment runoff conditions (USEPA, 2009).

1.2.2.2 2007 Navy Low Impact Development Policy for Storm Water Management

On November 16, 2007, the Navy issued a LID policy with a goal of "no net increase in stormwater runoff volume and sediment or nutrient loading from major renovation and construction projects" starting in 2011, to be achieved through the use of LID. It also implemented a service-wide policy mandating the use of LID on all projects with a stormwater element. For “those infrequent situations where LID is not appropriate,” a waiver process requiring “regional engineer level review and approval” is authorized (Navy, 2007).

1.2.2.3 Engineering & Construction Bulletin 2008-01 Energy Policy Act of 2005 Implementation and USGBC LEED Certification

The Navy’s Engineering and Construction Bulletin guidance document, *Energy Policy Act of 2005 Implementation and USGBC LEED Certification*, also provides guidance on the integration of LID into Navy projects. Specifically, this document states that all new buildings and major renovation projects where the work exceeds 50% of the building’s plant replacement value must meet LEED® Silver-level performance by incorporating specific strategies. These include LEED® Sustainable Sites Stormwater Design, quantity control (SS 6.1), quality control (SS 6.2), and water efficiency (WE 1.1 and WE 3.1) (NAVFAC, 2008). The most recent LEED® guidelines can be found in the document *LEED® 2009 for New Construction and Major Renovations* (USGBC, 2009).

1.2.2.4 Unified Facility Criteria (UFC) 3-210-10 Low Impact Development

The UFC system provides planning, design, construction, sustainment, restoration, and modernization criteria, and applies to the Military Departments, the Defense Agencies, and the DoD Field Activities. The latest UFC LID Manual, dated November 15, 2010, which supersedes an earlier (2004) version, provides technical criteria, technical requirements, and references for the planning and design of applicable projects to comply with stormwater requirements under Section 438 of the Energy Independence and Security Act (EISA) and the Navy's 2007 LID Policy for Stormwater Management. It establishes the basis for calculations by defining the hierarchy of standards and a recognized pre-development condition; defines rainfall for use in LID volume calculations (which is the larger of 95th percentile rainfall, or required water quality depth as design storm); and recommends that the TR-55 Curve Number Methodology be used to estimate runoff. It also states that any applicable state and local requirements for stormwater management shall be met in addition to UFC requirements (DoD, 2010).

1.2.2.5 Unified Facility Criteria (UFC) 1-200-02 High Performance and Sustainable Building Requirements

The UFC for High Performance and Sustainable Building Requirements, dated March 1, 2013, provides minimum unified requirements and coordinating guidance for planning, designing, constructing, renovating, and maintaining high performance and sustainable DoD facilities that are cost-effective. In order to promote sustainable location and site development in regards to stormwater management, the UFC primarily refers back to UFC 3-210-10. However, under the section addressing how to protect and conserve water, the subsection for outdoor water directs facilities to “use water efficient landscape and irrigation strategies, such as water reuse, xeriscaping, and the use of harvested rainwater, to reduce outdoor potable water consumption by a minimum of 50%. This requirement must be demonstrated by comparison to a baseline building using the USEPA WaterSense landscape water budget tool version 1.01 or later, or a Component approved tool.” This UFC supersedes UFC 4-030-01, dated December 2007, and UFC 3-400-01, dated July 2002, including Change 4, dated August 2008.

2.0 POLLUTANT LOADS

2.1 Common Activities at Focal Sites

Naval industrial activities often result in elevated heavy metals loads. Activities such as the grinding and sanding of metal parts, the application and removal of anti-fouling coatings, and the storage of scrap metal at recycling centers can all result in elevated discharges of a variety of metals. In addition, more ubiquitous metals sources common to a variety of land uses, such as vehicle traffic, leaching from metal building materials, and atmospheric deposition, add to metals loads. Metals loads can also be generated from chain link and security fencing, metal towers, and storm drain inlet grate structures. Typically, copper, lead, and zinc receive the most focus in stormwater, as they are common contaminants that are toxic to terrestrial and aquatic life at low doses.

2.1.1 Ship Building and Maintenance at Piers

Piers at naval bases are generally utilized to berth ships and support vessels and barges. Fueling and maintenance activities routinely occur on berthed vessels. Maintenance activities on docked vessels are varied and generally less complex than ship repair activities conducted at commercial shipyards or at graving docks or floating dry docks. Some repair activities that routinely occur pier-side may include abrasive blasting, hydro-blasting, metal grinding, painting, tank cleaning, removal of bilge and ballast water, removal of anti-fouling paint, sheet metal work, electrical and mechanical repair work, engine/ hull repair, and sewage disposal.

Shipyards are generally too large for a single end-of-pipe treatment strategy that collects and treats all stormwater; rather, a more distributed stormwater treatment strategy is more practical and allows stormwater BMPs to be selected and located based on the pollutant profile of a single activity.

In addition, ship repair work may also be conducted on the pier itself or at several repair shops usually located on the base. In these cases, parts are placed on the pier or adjacent land or are taken to the repair facility.

The maintenance of antifouling coatings on the hulls of ships is a major potential source of copper and zinc in stormwater. Most antifouling paints contain a copper-based biocide and a zinc-based booster (Jessop & Turner, 2011). Ship hulls are sanded to remove existing coatings prior to repainting, generating fine particles that can be difficult to contain. These particles can be carried off in stormwater, contaminating receiving waters.

Jessop & Turner studied the leaching of copper and zinc from small particles of boat paint into rainwater (2011). They found that the low pH of rainwater (typically pH 4-5) increased leaching as compared to pH-neutral tap water, and that copper and zinc leaching from the small particles increased with increasing contact time. Over 120 hours, rainwater had leached 3% of the total copper and 30% of the total zinc contained in the paint particles.

2.1.2 Ship Building and Maintenance at Dry Docks

Dry docks, also known as graving docks, are narrow concrete basins closed by gates or by caissons. A vessel may be floated into the concrete basin and the water pumped out, leaving the vessel supported by blocks. Dry docks are the primary way to perform major maintenance activities on submarines where a completely dry environment is required. However, they may also be utilized to perform complex repair activities on surface ships which may include hull repair and vessel conversions.

Nuclear powered submarines can also be serviced at dry docks. While in the dry dock, these submarines require an outside cooling water source that the facility will supply. This water is returned back to the source it was derived from and is usually not permitted to come into contact with any other system.

Because dry docks are impermeable surfaces that may span multiple acres, rain events can generate very large volumes of stormwater runoff, which may be heavily contaminated with metals generated by ship maintenance activities.

2.1.3 Marinas

Marinas are generally utilized to berth boats and smaller vessels. Maintenance activities that occur generally include boat rehabilitation, mechanical and electrical repairs, painting, fueling, and lubrication. The activities are less complex than those undertaken at the piers. The resulting pollutant loads should be small relative to other areas unless there are ongoing maintenance activities along the pier and marina that are treated (e.g., paint removal, cutting and welding, bottom cleaning, etc.).

2.1.4 Other Activities

In addition to the above activities that are specific to the major naval bases, other general activities common to military bases, such as material storage, equipment testing and repair, and weapons firing, frequently occur on naval bases. These activities also contribute to pollutant loadings at naval sites to differing degrees. However, a major difference is that these activities occur inland whereas the activities at piers and dry docks occur by water's edge. If the stormwater infrastructure is directly piped to surface water outfall, these activities can also lead to discharges of metals and other pollutants.

2.1.5 Materials Storage

Storing sheet metal and metal parts in uncovered areas leaves them exposed to the rain, which can cause metals to leach into stormwater.

A study of the leaching behavior of copper shingles measured annual runoff loads to be 0.6-1.7 g m² y⁻¹ at two sites in Sweden (Wallinder and Leygraf, 2001).

2.1.5.1 Recycling Centers

Recycling centers are places where scrap metals and other materials are collected for sorting and temporary storage prior to shipping separated materials to larger scrap metal dealers. Accumulated scrap metal is sometimes stored uncovered in parking lots, where rainfall can cause leaching from metal parts and wash off of smaller metal particles, such as filings. This can lead to extremely high metals concentrations in runoff. Concentrations of copper in scrapyards have been measured as high as 100 – 3,800 µg/L (National Research Council, 2008).

2.1.5.2 Landscape Materials

Stockpiles of used tires and shredded recycled tires (aka crumb rubber) can leach zinc into stormwater (Solano et al., 2012).

2.1.5.3 Atmospheric Deposition from Adjacent Sites

Atmospheric deposition can be a significant source of metals, particularly if sites are close to high traffic areas. Copper and zinc emitted in vehicle exhaust and component wear can become suspended in the atmosphere. The settling of suspended particles is referred to as dry deposition, and the washing of suspended particles out of the atmosphere by rainfall is known as wet deposition. Both dry and wet deposition are important contributors to metals loading in stormwater. Typical loading rates are highly variable, and depend on the distance to the roadway, traffic volume and congestion, the direction of prevailing winds, and rainfall patterns. As a result, metals loading attributable to atmospheric deposition will vary between sites.

Sabin et al. measured the contribution of wet and dry deposition to stormwater at a site in Los Angeles, CA (2005). They found the annual event mean concentration of copper in rainwater (wet deposition) to be 1 µg/l. The EMC of copper in stormwater at the site was 27 µg/l. Atmospheric deposition (wet + dry) accounted for 74% of the total copper loading in stormwater. In this semi-arid region, dry deposition was found to dominate over wet deposition. Thus, atmospheric deposition can be a major source of metals in urban areas.

Sabin et al. subsequently measured dry deposition rates of metals along a transect of coastal southern California, spanning the area between Santa Barbara and San Diego (2008). They found dry deposition rates to range from 0.89 to 29 µg-m²day⁻¹, with the highest rates observed at the San Diego Bay testing site. In general, higher deposition rates were associated with proximity to urban development.

2.2 Non-Industrial Sources of Copper Loading

In non-industrial areas, metals are released into stormwater through contact with automobiles and leaching from buildings. Copper is used as a wood preservative, and can leach from wooden structures, as well as from copper sheeting used as flashing, trim, and in rain gutters. Copper is also present in vehicle brake pads, which are subject to weathering over time, and accumulates in motor oil as it sits in contact with engine parts. Copper levels in runoff from urban areas are typically in the range of 5-200 µg/l. Brake wear is the dominant source of copper (about 50%) in most urban residential stormwater runoff, while roofing is the dominant source of copper (approx. 75%) in urban commercial stormwater runoff. Annual loadings have been estimated to

be an order of magnitude higher for commercial land uses than for residential land uses (0.243 kg/ha-yr vs. 0.033 kg/ha-yr). Davis, Shokouhian, and Ni present a thorough analysis of the sources and loading rates of copper in urban stormwater (Davis et al., 2001).

2.2.1 Copper Speciation in Stormwater

Copper occurs in both particulate and dissolved forms in stormwater. The ratio of particulate to dissolved fractions depends on the water chemistry, in particular, residence time, pH, redox potential, and the affinity of suspended solids for copper. As pH decreases, copper tends to remain dissolved in solution (the dissolved fraction increases). Dissolved copper is the most bioavailable, and therefore the most toxic to aquatic biota (USEPA, 2007).

Copper partitioning in stormwater has been evaluated in a number of studies (Sansalone and Buchberger, 1997; Sauvé et al., 2000; Li and Davis, 2009). Dissolved copper has a strong tendency to form complexes with aqueous hydroxides, carbonates, and dissolved organic matter. Dominant copper complexes vary with hydrology, pH, and with which ligands are present in the stormwater. Suave et al. and Dean et al. measured dissolved copper speciation in stormwater, finding that a majority of dissolved copper was present in complexed form (2000; 2005).

2.3 Nitrogen and Phosphorus

Nitrogen and phosphorus have become pollutants of great concern in many watersheds around the country. Because they are major plant nutrients, discharges can stimulate the overgrowth of algae and phytoplankton. This process is known as eutrophication, and results in a severe degradation of water quality, especially depletion of oxygen in the water column as dead algae sink and are consumed by bacteria. For this reason, nitrogen and phosphorus discharges are beginning to be regulated, most notably in the watershed of the Chesapeake Bay, which is struggling with low oxygen levels caused by excessive nutrient enrichment.

2.3.1 Nitrogen Loading in Stormwater

A principal source of nitrogen in stormwater is fertilizer, which is applied to lawns and other landscaped areas. This fertilizer is frequently over-applied, and is prone to wash-off during storm events. Vehicle exhaust is also a major source of nitrogen in stormwater, as nitrogen compounds emitted into the atmosphere are deposited on impermeable surfaces (dry deposition) or washed out of the air by rainfall (wet deposition). Plant debris and detritus can also be an important nitrogen source. Additional, usually more minor, sources of nitrogen include waste from pets and wild animals. Khwanboonbumpen presents a thorough accounting of the sources of nitrogen in urban stormwater (2006).

Sources of Nitrogen in Industrial Areas

- Fertilizer, compost, and topsoil storage areas
- Large managed turf areas
- Atmospheric deposition, particularly in urban areas and areas near freeways

2.3.2 Nitrogen Chemistry in Stormwater

Nitrogen is present in stormwater in a variety of forms, depending on the source of the pollutant, as well as the stormwater pH and redox potential. Nitrogen is discharged into stormwater in the form of a variety of organic compounds, including urea and proteins, as well as inorganic forms (ammonium, NH_4^+ ; nitrite, NO_2^- ; and nitrate, NO_3^-).

In aerobic waters, microbes transform ammonium to nitrite (NO_2^-), and eventually to nitrate (NO_3^-). Nitrate is readily taken up by plants and algae, but does not adsorb to suspended particles or form complexes or precipitates (Davis and Mccuen, 2005). Under anaerobic conditions, microbes can transform nitrate to nitrogen gas (N_2).

Soluble organic nitrogen (SON) is a chemically complex family of nitrogen-containing soluble organic compounds, which may make up a sizeable fraction of the nitrogen leached from soils. The potential importance of this form of nitrogen has only recently been recognized, and research is ongoing to determine how SON moves through soils, and which removal strategies may be most effective (Brady and Weil, 2002).

2.3.3 Phosphorus Loading in Stormwater

Phosphorus in stormwater primarily comes from fertilizers used in landscaped areas. It can also come from phosphate-based detergents used in car washing, pet wastes, and plant debris. Atmospheric deposition of phosphorus is less than that of nitrogen, but still occurs as the result of the burning of fossil fuels, as well as the suspension of phosphorus-rich soil dusts in the atmosphere. Phosphates have also been found to leach from a variety of roofing materials, in particular asphalt shingles, roofing felt, galvanized metal, and pressure treated wood (Clark et al., 2008).

Sources of Phosphorus in Industrial Areas

- Fertilizer, compost, and topsoil storage areas
- Large managed turf areas
- Atmospheric deposition, particularly in urban areas, high traffic areas, or areas close to eroding soils
- Roofs
- Galvanized metal parts and other building materials stored in uncovered areas
- Detergents used in washing of vehicles, equipment, and boats

2.3.4 Phosphorus Chemistry in Stormwater

Phosphorus is present in soluble and particulate forms. Depending on the source, phosphorus can be present in inorganic and organic forms. The most common form of phosphorus in stormwater is phosphate, usually H_2PO_4^- and HPO_4^{2-} , depending on pH (Stumm and Morgan, 1996). Phosphates have a strong tendency to bind with soil particles, and are therefore predominantly found in the solid fraction of stormwater (Davis and Mccuen, 2005).

3.0 STORMWATER POLLUTANT REMOVAL

3.1 Copper Removal Pathways – Unit Processes

Removal of copper from stormwater is complicated by the fact that copper is present in a variety of forms. The majority of copper is typically in dissolved form, but as discussed previously, copper readily forms complexes with a variety of dissolved ligands, most commonly dissolved organic matter (DOM), carbonates, and hydroxides. The relative proportions of these different forms vary according to runoff pH, ligand concentrations, runoff intensity, and residence time.

This complexity and variability necessitates the use of stormwater treatment methodologies that combine a variety of physical and chemical unit processes to remove copper in each of the forms in which it may be present. In general, the higher the charge of an ion or dissolved molecule, the more strongly it will adsorb onto the media. For this reason, complexed dissolved copper, which tends to be neutral or monovalent, may be more difficult to remove from solution than divalent ionic copper. Media with a more complex and heterogeneous chemical composition, such as peat moss and compost, may be able to provide enhanced removal because they contain a variety of different sorption and ion exchange sites.

More detailed discussion of metals removal mechanisms can be found in Pitt and Clark; and Li and Davis respectively (2010; 2008).

Table 3-1. Unit Processes for Copper Removal

Particulate-Bound Copper	Dissolved Copper
<ul style="list-style-type: none">• Settling• Filtration	<ul style="list-style-type: none">• Sorption• Ion exchange• Precipitation (which renders it particulate)• Plant uptake• Complexation

3.1.1 Settling and Filtration of Solid Particles

Removal of particulate-associated copper is achieved through filtration. Metals have higher affinity for smaller particles, which have proportionally higher surface areas and higher cation exchange capacities (Herngren et al., 2005). The proportion of copper occurring in dissolved vs particulate states is highly dependent upon the chemical makeup of the stormwater. In situations where a large proportion of copper is found to be in a particulate-bound form, the use of pretreatment involving settling and/or filtration can remove a large proportion of the copper load.

3.1.2 Sorption

Copper ions can adsorb to particles, such as humified organic matter and clays. This can occur in runoff prior to treatment, as copper adsorbs onto suspended particles carried along in stormwater, and is also a major mechanism in the removal of dissolved copper as it passes through filter media. Studies on the sorption and retention of Cu^{2+} in soils have found that sorption and retention of Cu^{2+} is most influenced by soil pH, cation exchange capacity (CEC), and iron and manganese oxide contents.

Cerqueira et al. and Dong & Wang have conducted experimental studies of the transport and mobility of copper as it is transported through soils (2011; 2012).

3.1.3 Binding with Iron and Manganese Oxides

Copper has a high affinity for iron and manganese oxides, and will readily bind to the surface of particles containing them. Clay particles in natural soils tend to be coated with oxides and organic matter.

Cerqueira et al. found that copper sorption and retention in soils was highly correlated with manganese oxide content (2011). Pitt and Clark found that increasing the iron concentration of the media improved copper removal (2010).

3.1.4 Plant Uptake

Copper is a micronutrient, necessary in minute quantities for plant life. All plants have some ability to uptake copper from the soil. Copper in higher doses, however, can be toxic to most plants. Certain *hyperaccumulator* plant species have the ability to take up large amounts of copper and build up high concentrations of copper in their tissues. Phytoremediation of heavy metals is covered in detail in Ali et al. (2013).

3.1.5 Formation of Complexes with Organic Matter

As previously discussed, copper has a strong affinity for organic matter. When this organic matter is part of the media matrix, complexed copper is removed from solution. As this organic matter decays, however, dissolved organic matter (DOM) can build up in the media pore water. When the media is subsequently inundated, this DOM, along with its complexed copper, can be washed out of the system. Copper that is complexed with DOM is harder to remove from solution than free or inorganically-complexed dissolved copper, but may be less toxic to fish and invertebrates.

These phenomena are discussed in detail in Johnson et al. (2003), Pitt and Clark (2010), Zhao et al. (2007), Sauvé et al. (2000), Yin et al. (2002), and Li and Davis (2009).

3.1.6 Formation of Complexes with Carbonates

Copper can bind to carbonates present in the water and soil. Carbonates that are neutral or negatively charged have a reduced ability to bind to the copper and form a precipitate that can be filtered from the stormwater.

3.1.7 Complicating Factors

Research into copper chemistry has turned up recurring factors that complicate copper removal. In addition to copper, lead and zinc are metals that are typically found in stormwater runoff. In industrial applications, other metals can include chromium, nickel, cadmium, arsenic, mercury, and more. These factors are discussed in the following sections.

3.1.8 Dependence on pH

In general, as pH decreases, metal solubility increases. Decreasing pH can cause metals to desorb from soil particles. Increasing pH, however, increases DOM concentrations, and may lead to leaching of copper complexed with DOM. This is discussed in Yin et al. (2002).

3.1.8.1 Redox Potential

Copper is less soluble in its oxidized form Cu^{2+} than in its reduced form, Cu^+ ; therefore, maintaining aerobic soil conditions will help to minimize copper leaching (Brady and Weil, 2002).

3.1.8.2 Competition with Other Metals

In most stormwater, copper is only one of several metals present. In addition to copper, common runoff metals are lead and zinc. In industrial applications, other metals can include chromium, nickel, cadmium, arsenic, mercury, and more. These metals compete with one another for sorption sites in the filtration medium.

3.1.8.3 Ion Exchange Considerations

As the name implies, ion exchange reactions involve the release of a bound ion in preference for another ion present in solution. It is important to consider what ions these exchanges will release (see p. 261 of Pitt and Clark (2010) for discussion of trade-offs). Dissolved metals and nutrients can be removed via both anion and cation exchanges within the media matrix. In these exchanges, the metals and nutrients become bound into the matrix, but other ions are released. In some cases, these ions may be pollutants. For example, in high-phosphate media, phosphorus is frequently released as a result of ion exchange reactions. Ion exchanges can also result in shifts in media pH, which may impact the mobility of various pollutants.

3.2 Nitrogen Removal Pathways

Nitrogen removal differs from removal of copper and phosphorus in that biological processes play the dominant role. Nitrogen undergoes a series of transformations that convert it from its original form in stormwater to its final form when it is removed from the treated effluent. These transformations are carried out by microbes, with the assistance of physical and chemical processes. Nitrogen removed from stormwater can be stored within a soil medium, plant biomass, or it can be released to the atmosphere.

Table 3-2. Unit Processes for Nitrogen Removal

	Particulate-Bound Nitrogen	Dissolved Nitrogen
Intermediate capture / Transformation processes	Settling Filtration	Sorption Ion exchange Ammonification Nitrification Microbial immobilization
Ultimate removal processes	Transformation and removal via the same processes as dissolved nitrogen	Ammonia volatilization Plant uptake (if plants are removed) Denitrification

3.2.1 Ammonification

Organic nitrogen compounds in stormwater, such as urea, are converted to ammonium by soil microbes. This process is referred to as ammonification, and occurs over the course of a few days under aerobic conditions, likely between storm events.

3.2.2 Sorption of Ammonium

Ammonium ions are positively charged, and are therefore readily sorbed to negatively charged clay and humus in the soil. 2:1 type clays, such as vermiculite, have the additional capacity to tightly bind ammonium within cavities in their crystalline structures, rendering them much less available for ion exchange.

3.2.3 Ammonia Volatilization

At very high pH levels (>9), especially under low-moisture conditions, ammonium ions can react with available hydroxide ions (OH⁻) to form gaseous ammonia (NH₃), which is released to the atmosphere.

3.2.4 Nitrification

Under aerobic conditions, ammonium ions in the soil are converted to nitrate by nitrifying bacteria. Nitrate's negative electrostatic charge allows it to flow freely through soils, which contain predominantly negatively charged particles. This greatly complicates its capture and removal.

3.2.5 Plant Uptake

Nitrogen is an essential macronutrient, and is readily taken up by plant roots. The principal forms taken up by plant roots are nitrate and ammonium.

3.2.6 Immobilization

Soil microbes require nitrogen to grow and multiply. Some of this nitrogen requirement is satisfied by consuming organic nitrogen from decaying soil organic matter. However, when the nitrogen content of soil organic matter is low, microbes can make use of mineral forms of nitrogen, such as nitrate and ammonium. This nitrogen is taken up by microbes and stored in proteins in microbial tissues in a process known as immobilization.

These processes are covered in detail in chapters 12 and 13 of Brady and Weil (2002).

3.2.7 Denitrification

Under anoxic conditions, certain bacteria can use nitrate as an electron acceptor, reducing nitrate to nitrogen gas. This process is known as denitrification. Denitrification requires oxygen levels lower than 10%, as well as a carbon source to provide an electron donor and energy to the denitrifying bacteria. These conditions frequently exist in microsites within otherwise aerated soils, permitting denitrification.

Note that the process can produce nitrous oxide (N_2O) rather than dinitrogen gas (N_2) under conditions where nitrate levels are high, pH is low, and some oxygen is available. This is a potential concern, as N_2O is a potent greenhouse gas, depletes the ozone layer, and contributes to atmospheric pollution.

These processes are described in detail in Brady and Weil (2002).

3.2.8 Complicating Factors

Variables in field conditions may severely impact the performance of systems. The range of pH, presence of oxygen, and thermal conditions must be considered in the selection of the systems.

3.2.8.1 *pH*

The optimum pH for denitrification is 7 to 8, with the rate dropping off significantly at pH values lower than 6 or higher than 8 (Kadlec and Knight, 1996). The process of nitrification releases H^+ ions, reducing soil pH. Optimal nitrification takes place at pH values between 6.6 and 9.0 (Kadlec and Knight, 1996).

3.2.8.2 *Oxygen*

The presence or absence of oxygen in the soil determines which nitrogen reactions can take place. Nitrifying bacteria need oxygen to carry out the necessary reactions to convert ammonium to nitrate; therefore, nitrification will only occur in media with high oxygen content. Conversely, denitrifying bacteria requires the absence of oxygen in order to convert nitrate to dinitrogen gas. Anoxic conditions develop only in places where water has been stagnant and out of contact with the atmosphere for long enough for aerobic bacteria to deplete the oxygen naturally present in the water. These conditions may take hours to days to develop.

3.2.8.3 Temperature

Since nitrogen removal is a microbially-mediated process, it is highly dependent upon temperature. All of the major bacteria involved in nitrogen cycling are best adapted to moderate temperatures. Their metabolism decreases as soil temperatures fall in cold weather. The optimal temperature range for nitrification is 25 to 35°C (77 to 95°F), with nitrification rates declining sharply below 15°C (59°F) (Kadlec and Knight, 1996).

3.3 Phosphorus Removal Pathways

Phosphorus is removed principally through binding and sorption to various media (Kröger et al., 2013). Phosphates are negatively charged anions, and are therefore removed by different pathways than positively-charged metal cations. Phosphorus is naturally present in soils in both organic and inorganic forms. Most of the phosphorus is held tightly by the medium, and is only very slowly released.

Table 3-3. Unit Processes for Phosphorus Removal

Particulate-Bound Phosphorus	Dissolved Phosphorus
Settling Filtration	Sorption Ion exchange Precipitation (which renders it particulate) Plant uptake Immobilization

3.3.1 Settling and Filtration

Settling and filtration are used to remove suspended particulate phosphorus from stormwater. Pretreatment technologies that rely on settling and filtration can remove a large proportion of phosphorus loads.

3.3.2 Binding and Precipitation

In acidic soils, phosphate binds with dissolved Fe^{3+} , Al^{3+} , and Mn^{2+} ions, forming insoluble hydroxyl phosphate precipitates (Brady and Weil, 2002).

3.3.3 Sorption

In neutral soils, sorption to kaolinite clays is important. The soils potential for sorbing phosphorus is dependent on texture and clay mineralogy and increases with clay content. Research at the University of Minnesota's St. Anthony Falls Laboratory uses a steel wool or elemental iron added to a sand filter to allow dissolved phosphorus to bind to the oxides, now referred to as the Minnesota Filter (Erickson et al., 2012).

3.3.4 Plant Uptake

Orthophosphate is the most readily available form of phosphorus for plant uptake. Microbes in the soil convert organic phosphorus into inorganic forms, making it available to plants. Phosphorus is a major nutrient, essential for plant growth. The rate of phosphorus uptake can vary with environmental conditions and plant species. Mycorrhizal fungi can increase the availability of phosphorus to plants, and can thereby boost the rate of phosphorus uptake in associated plants.

3.3.5 Immobilization by Microbes

Microbes can also incorporate soluble orthophosphate directly into their tissues. This increase of microbial biomass within the media represents a temporary immobilization of phosphorus within the soil medium.

3.3.6 Complicating Factors

The influence of concentrations and presence of many substances and processes have the potential to impact the efficiency and effectiveness of BMP systems. Mixing and/or reactions of other contaminants in stormwater, pH, loading, temperature, and buffering are some of the considerations for system design. Many forms of natural organic matter and leach phosphorus and can act as a phosphorus source when placed in a BMP.

3.3.6.1 *pH*

Phosphorus removal is strongly influenced by pH. Phosphorus fixation is lowest at near neutral pH (6-7) (the ideal environment for growth), and greatest at extremely low and high pH values.

3.3.6.2 *Phosphorus Index*

The quantity of phosphorus already present in a soil or other medium has a marked effect on phosphorus removal. The phosphorus index, p-index, is an indicator of a soil's remaining capacity to adsorb phosphorus. A low p-index indicates a high capacity to adsorb additional phosphorus, while a high p-index indicates a soil already saturated with phosphorus. Soils with high p-indexes cannot adsorb phosphorus from percolating stormwater, and will often even leach phosphorus. This phenomenon is covered in Hunt et al. (2006).

3.3.6.3 *Organic Matter*

Organic matter has relatively little ability to fix phosphate, and more commonly serves as a source of phosphate as it decomposes. High organic content can even interfere with phosphorus retention in a number of ways. Organic matter can adhere to the surfaces of clays and metal oxides, preventing phosphorus from contacting these potential binding sites. Dissolved organic matter can compete with phosphate for binding sites, and can also form chelates with aluminum and iron, effectively preventing them from reacting with phosphorus.

3.3.6.4 Redox Potential

Phosphorus that is bound to iron oxide precipitates can be released when anaerobic conditions develop in a soil. Iron becomes reduced, dissolving the iron oxide and releasing the phosphorus that was attached to it. This could be a cause of phosphorus leaching from media that incorporate anaerobic zones to enhance nitrogen removal.

3.4 Comparison of BMPs with Respect to Unit Processes

Breaking down the removal of pollutants into various unit processes allows us to compare the potential pollutant removal performance of various BMPs by examining which unit processes they incorporate. A similar approach is presented in Scholes et al. (2008). Table 3-4 summarizes which unit processes are important for the removal of copper, nitrogen, and phosphorus.

Table 3-5 indicates which of these unit processes are employed by several of the most common LID-type stormwater BMPs. Modifications or enhancements to these BMPs can add to the number and type of unit processes.

Table 3-4. Summary of the Unit Processes Contributing to the Removal of Copper, Nitrogen, and Phosphorus from Stormwater

Unit Processes	Copper	Nitrogen	Phosphorus
Settling	X	X	X
Filtration	X	X	X
Sorption & Ion exchange	X	X	X
Precipitation	X		X
Complexation	X		
Volatilization		X	
Microbial immobilization		X	X
Microbial transformation: - Ammonification - Nitrification - Denitrification		X	
Plant uptake	X	X	X

Table 3-5. Comparison of the Unit Processes Employed by the Most Common LID Stormwater BMPs

Unit Process	Bioretention /Biofilter	Vegetated Swale	Permeable Pavement	Green Roof	Sand Filter	Infiltration Trench	Constructed Wetland	Filter Strip	Infiltration Basin
Settling	X	X					X	X	X
Filtration & Ion exchange	X	X	X	X	X	X	X	X	X
Sorption	X	X		X			X	X	X
Precipitation	X						X	X	X
Complexation	X	X		X			X	X	X
Volatilization	X						X	X	X
Microbial immobilization	X	X	X	X	X	X	X	X	X
Microbial transformation:									
- Ammonification	X	X	X	X	X	X	X	X	X
- Nitrification	X	X	X	X	X	X	X	X	X
- Denitrification	X						X		
Plant uptake	X	X		X			X	X	X

4.0 PERFORMANCE OF BIORETENTION AND OTHER MEDIA-BASED FILTERING SYSTEMS

Several LID systems have the potential to remove or decrease stormwater pollutant loads. The focus of this section is on the ability of the systems to treat metals in stormwater runoff. The treatment of lead and zinc and the hydrologic performance may be addressed in subsequent revisions of the literature review. It should be noted that many of the studies included in this review also address these pollutants. The advantage of using LID systems is that many of the physical, biological, and chemical treatment processes can be modified through actions such as sizing, detention and storage volumes, and customized media mixes. Filtering and retention based systems, such as bioretention, bioswales, and biofilters, have the most potential to be adapted for metals treatment.

4.1 Description

Bioretention receives unique attention among LID BMPs because of its potential to exploit all of the unit removal processes described in Chapter 3 of this document, while also reducing stormwater volume by means of infiltration and evapotranspiration.

Bioretention achieves pollutant removal through a combination of physical, chemical, and biological processes. Pollutant removal performance can be optimized by adjusting a number of design factors, including the composition of the filter media, plant selection, and drainage characteristics.

The chemistry of all three of the pollutant groups reviewed is complex, and optimizing bioretention for their removal has yielded variable results as researchers have gradually learned which media and design configurations work best. Very good to excellent removal has been achieved for all three pollutants, but low treatment efficiencies and even pollutant export have also been reported. These results show that bioretention has the potential to provide excellent water quality treatment, but can in some cases degrade water quality. Learning to design effective bioretention systems requires understanding and working with the complex chemistry of the targeted pollutants, and has necessitated laboratory and field scale testing of multiple design variations under a range of environmental conditions.

Three review papers discussing the overall performance of bioretention have been published to date (Hunt et al., 2012; Davis et al., 2009; Dietz, 2007).

Percent mass removal is often the preferred metric when considering pollutant load reductions to receiving surface waters, because it takes into account volume reductions in stormwater resulting from evapotranspiration and infiltration (Davis, 2007). In this analysis, we are interested in the ability of bioretention to capture and remove pollutants. At the high loading rates experienced at Navy sites, infiltration of treated stormwater that still contains a relatively high concentration of copper and/or nutrients could lead to groundwater contamination. Therefore, effluent concentration may be a better metric by which to evaluate performance.

Percent removal is not considered, as its usefulness and accuracy as a performance metric for bioretention has been questioned by multiple studies (McNett et al., 2011, Blecken et al., 2007).

McNett et al. compared influent and effluent concentrations of total nitrogen (TN) and total phosphorus (TP) to see if effluent concentrations showed any dependence on influent concentrations (2011). They found that effluent TP was largely independent of influent concentration. Given a medium of sufficient depth, effluent TP seems to be largely determined by the amount of phosphorus present in the medium. The media will remove phosphorus from solution until the solution phosphorus concentration comes into equilibrium with the sorbed phosphorus. This equilibrium determines the minimum possible effluent TP concentration.

Nitrogen is removed principally by biological rather than physicochemical processes, and removal is dependent on long residence times. Bioretention designs that do not provide sufficient contact time for stormwater with high TN are not able to reduce effluent TN to the minimum achievable baseline TN for that particular design.

When looking at these numbers, it is also important to compare influent and effluent copper concentrations between test sites. Metal removal tends to increase as inflow concentration increases. The lowest attainable effluent copper concentration may give a better sense of how well the BMP can perform (Muthanna, Viklander, et al., 2007).

In addition to copper, removal of lead and zinc has been demonstrated in bioretention and biofilters (Johnson et al., 2003; Davis et al., 2003; Davis and Li, 2008). Lead has a very high affinity for soil and dust particles, and is readily filtered and sorbed in biofilters. Zinc removal has been more variable due to the complex chemistry of zinc in stormwater, similar to the behavior of copper (Johnson et al., 2003).

Bioretention cells have been shown to produce significant reductions in stormwater volume, even when underdrains are used (Hunt et al., 2012). The ability of bioretention cells to reduce stormwater volume in addition to improving water quality makes bioretention a potentially more powerful BMP than the use of biofilters, which can only improve water quality. Bioretention, however, requires more space than biofilters, and is not suitable for use on all sites.

4.2 Copper Removal

Tests of biofiltration systems have yielded variable copper removal performance. In some cases, tests report copper removal rates of 90% or greater, while others report much lower removal performance, and occasionally even copper export. As has been discussed, this is owing to the complexity of copper chemistry and its sensitivity to pH, organic matter content and characteristics, and other environmental factors.

An innovative filtration system was developed and tested by the Naval Facilities Engineering Service Center (NAVFAC ESC). The filter was designed to remove metals from stormwater runoff from DoD industrial sites, and was tested at the Navy Regional Recycling Center (NRRC) at Naval Station San Diego, and at the Defense Reutilization and Marketing Office (DRMO) at Anniston Army Depot (ANAD). Both sites are involved in metal scrap recycling. The filters used a layered combination of bone char and surface modified activated alumina. This media mixture removes metals through filtration and adsorption. The system was able to achieve greater than

80% removal of metals at both testing sites. Copper was reduced to non-detect levels for the majority of storm events at ANAD. However, the filters were found to be susceptible to clogging with sediment. The researchers therefore recommend the use of a pretreatment stage to remove suspended sediment prior to filtration, or annual removal and replacement of the top filter medium, where fine particles tend to become trapped.

In a study funded by the Water Environment Research Foundation (WERF), Johnson et al. tested several candidate media in order to assess metals removal performance (2003). In-depth studies were performed on the three best performing media: peat-sand mix, compost, and zeolite. The peat-sand mix exhibited the best metal capture performance, but was prone to clogging. Compost had the second best metal capture performance, but tends to leach nutrients and dissolved organic matter. Zeolite had lower metal removal performance, but is prone to neither clogging nor leaching. The study includes a comprehensive overview of metals removal mechanisms, and informed much of this literature review. A second component of the study looked at metals removal in bioswales. Bioswales were planted with several grass varieties to enhance uptake of metals. Centipedegrass, common in the southeast, was found to have the highest capacity to uptake metals.

4.2.1 Variables That Can Impact Copper Removal

Several factors can affect the performance of BMPs, including site- and storm-specific factors as well as variations in biofilter design. The design of the system must account for variability and uncertainty in stormwater loads. The most important factors influencing copper removal are discussed in this section.

4.2.1.1 *Inflow Concentration*

Copper removal rates are linked to inflow concentrations. Outflow concentrations are positively correlated with inflow concentrations (Blecken et al., 2009). The majority of copper removal takes place through sorption and filtration in the uppermost media layers (Li and Davis, 2008). At very low inflow concentrations, the copper concentration may be so low at the bottom of the media as to cause desorption of copper from the media (Li and Davis, 2009, 2008). Muthanna, Gjesdahl, et al. tested copper leaching from bioretention media using deionized water as the inflow and found effluent copper levels of 30-40 µg/L (2007).

4.2.1.2 *Organic Matter*

A large proportion of heavy metals removal takes place in the surface mulch layer (Davis, Shokouhian, Himanshu, et al., 2001; Muthanna, Viklander, et al., 2007). Copper has a strong tendency to associate with organic matter, both in particulate and dissolved forms (Sauvé et al., 2000). Li and Davis found that the partition coefficient (K_d) of copper was much higher in the effluent than the input for the bioretention cells they examined, indicating that more copper was present in dissolved form in the effluent than in the inflow (2009). They speculate that this may have been partly the result of influent copper binding with organic matter in the bioretention cell, which was subsequently dissolved from the media and washed out. Muthanna, Viklander, et al. also observed an increase in dissolved copper as runoff passed through the bioretention cell (2007).

Copper has a high affinity for soil organic matter (SOM). Increasing SOM tends to decrease the dissolved copper fraction (Sauvé et al., 2000).

Li and Davis sampled stormwater inflow and outflow from two bioretention cells to determine the proportion of copper in dissolved and particulate fractions (2009). They found the dissolved fraction (f_d) to range from 0.27-0.40, with no significant difference between inflow and outflow. However, they found a significant increase in K_d in the bioretention effluent, indicating that a greater proportion of copper became particulate-bound as a result of passing through the bioretention cell. This was attributed to the observed leaching of organic matter from the cells, which has a very high affinity for dissolved metals. Thus, a high proportion of the copper in the effluent is tightly bound to particulates and/or organic matter, and a lower proportion of the effluent copper is present in the more highly toxic dissolved form. This suggests that bioretention treatment may lower effluent copper toxicity even where it fails to remove copper completely. Hunt et al. stress that the mulch layer is critical to metals removal in bioretention cells (2012).

4.2.1.3 pH

Davis et al. tested the effect of varying pH on copper removal, and found no significant difference in effluent copper concentrations as the influent pH varied from 6 to 8 (2003). Pitt and Clark observed a decrease in copper removal as pH increased above neutral (2010).

4.2.1.4 Media Depth

Most metal removal occurs in the top layer of the filter media (Muthanna, Viklander, et al., 2007; Davis, Shokouhian, Sharma, et al., 2001; Hatt et al., 2009). Modeling and field testing by Li and Davis suggest that most metal removal takes place in the uppermost 10-20 cm of the bioretention media (2008). They therefore suggest that in situations where metals removal is the principal concern, bioretention media depth can be reduced to 20-40 cm.

4.2.1.5 Variations in Soil Moisture (Intermittent Wetting and Drying)

Blecken et al. tested the effect of up to 7 weeks of drying time on the metals removal performance of a biofilter during subsequent storm events (2007). They found that copper outflow concentrations became elevated after drying periods of at least 3 weeks. Reasons that drying might reduce copper removal include (as identified by (Blecken et al., 2007)):

- Decreased removal during the first storm after drying due to the creation of preferential flow paths through media
- Reduced plant metal uptake due to plant stress
- Flushed dead root cells and microorganisms
- Decreased soil moisture causing trapped metals to oxidize, which are then flushed in subsequent storm events

4.2.2 Design Variations to Improve Copper Removal

The following design modifications are suggested based on published studies and our current understanding of copper removal mechanisms.

4.2.2.1 Use of Low Copper Content Media

The copper content of the media appears to limit the ability of bioretention media to achieve extremely low effluent copper concentrations, since inflow with very low copper concentrations will prompt desorption of copper from the media in order to maintain chemical equilibrium (Stumm and Morgan, 1996, Li and Davis, 2008). This effect can be reduced by using media with a low copper content.

4.2.2.2 Reducing Media Depth

Since the majority of the copper removal takes place in the uppermost 10-20 cm, Li and Davis recommend limiting the depth of bioretention cells focused on metals capture to 20-40 cm (2008).

4.2.2.3 Use of a Submerged Zone

While excellent removal of heavy metals by bioretention media is generally noted, Blecken et al. found that copper removal was impacted by prolonged drying in between storms (2009b). This effect could be eliminated by incorporating a submerged zone into the biofilter design. Copper outflow concentrations were consistently about 12 µg/l lower and removal rates were 12% higher for the columns incorporating a submerged zone. Clark and Pitt tested metals leaching from a variety of stormwater treatment media and found that metals which had sorbed to media under aerobic conditions were not released when the media was exposed to anaerobic conditions (2009). Overall, the use of a submerged zone does not appear to reduce the strong metals removal performance of bioretention systems. It may be useful to include this design feature for the treatment of other pollutants, such as nitrogen.

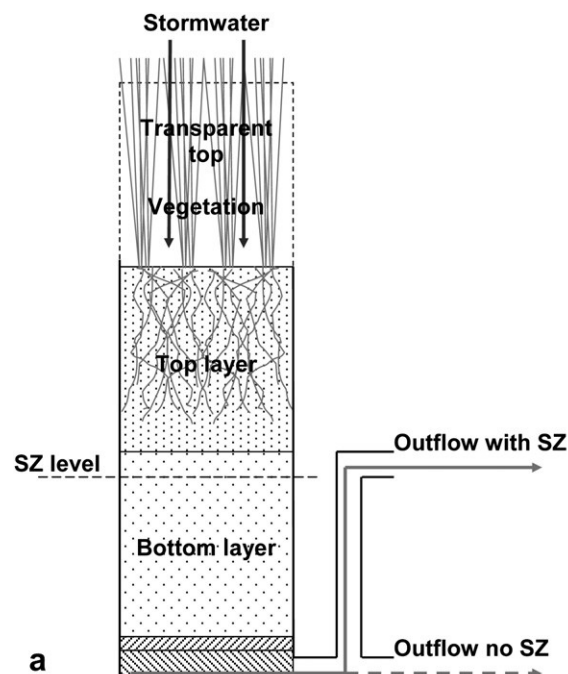


Figure 4-1. Biofilter Setup with Submerged Zone, as Tested by Blecken et al. (2009c)

4.2.2.4 Addition of Organic Matter

The biofilters tested by Blecken et al. used a layered media composed of a sandy loam top layer and a fine sand bottom layer (2009c). These showed good copper removal performance, but those that incorporated a submerged zone, as shown in Figure 4-1, also incorporated a carbon source (a mixture of wood chips and pea straw), which was mixed into the bottom layer sand. This organic matter is likely to have played a role in the improved copper removal performance of the biofilters using the submerged zone design. Pitt and Clark saw an increase in removal of filtered copper as organic matter (OM) and CEC increased (2010).

4.2.2.5 Use of Alternate Soil Media

Pitt and Clark tested a variety of biofilter media mixtures (2010). Their top performer, a mixture of Rhyolite sand (30% by volume), surface modified zeolite (30%), granular activated carbon (30%), and peat (10%), met site discharge limits for metals at low concentrations, but failed when the influent copper concentration was higher than 100 $\mu\text{g/l}$.

4.2.2.6 Addition of Biochar

Biochar is a material produced by pyrolysis of organic feedstock under oxygen-limited conditions. It is a low-cost material that can be made from a variety of organic wastes, including crop residues, wood, and even manures. Biochar has been shown to have an adsorption capacity equal to or greater than that of activated carbon (Tong et al., 2011). Chemical properties are governed by feedstock characteristics and pyrolysis conditions, especially temperature.

Biochar is receiving increased interest for its potential use as a method to sequester carbon, and for its potential effects on greenhouse gases emitted from soils. Biochar added to soils has been shown to reduce emissions of methane and nitrous oxide, both potent greenhouse gases.

Cu^{2+} can adsorb electrostatically to biochar, and can also form surface complexes with hydroxyl (-OH) and carboxyl (-COOH) groups present on biochar surfaces (Tong et al., 2011). Biochar also readily adsorbs dissolved organic carbon, and therefore can also bind copper that is complexed with dissolved organic matter.

Karami et al. tested the ability of biochar to immobilize copper when used to amend highly contaminated soils, and found that the addition of biochar reduced the amount of copper leaching into pore water, and the concentration of copper found in plant biomass grown on the amended soil (2011).

Biochar can be created from a variety of feedstocks, using a variety of methods. The effects of these methods on the ability of biochar to adsorb metals is an area of active research (Regmi et al., 2012; Beesley et al., 2010; Nelms and Connelly, 2006; Tong et al., 2011; Trakal et al., 2013; Kołodyńska et al., 2012).

4.3 Nitrogen Removal

Studies that examine the dynamics of nitrogen chemistry in biofilters typically find that they achieve excellent reductions in ammonium and organic nitrogen, principally through capture and microbial conversion processes (ammonification and nitrification). These two processes can take place in aerobic environments, and the microbes responsible for these conversions are ubiquitous in the environment, and readily colonize a variety of substrates. Nitrate reduction, however, is much more variable. Nitrification converts positively charged ammonium (NH_4^+) into negatively charged nitrate (NO_3^-). Nitrate's negative charge renders it highly mobile in most biofilter media, which typically have a high affinity for cations, but low affinity for anions. Unless nitrate is taken up by plants or converted through denitrification, a large percentage of the nitrate produced in the media will pass through the system. Denitrification, in which bacteria convert nitrate to gaseous dinitrogen, is an anaerobic process that can only take place in the absence of oxygen, a condition that is not included in every biofiltration design.

4.3.1 Variables that Can Impact Nitrogen Removal Performance

An extensive search through published literature has indicated that nitrogen removal is dependent on the variables discussed in this section.

4.3.1.1 Leaching from Breakdown of Organic Matter in Media

Brown and Hunt observed nitrate leaching from standard bioretention cells (without anaerobic zones) (2011). Over several months of monitoring after construction, they observed no increase in nitrate outflow concentrations over the first two months, followed by a large spike in outflow nitrate concentrations over the following four months (Jul-Nov), and then a return to “normal” for the final four months (Dec-Mar). The researchers attribute this spike to leaching from the mulch, as had been previously observed by Hsieh and Davis (2005).

4.3.1.2 Vegetation

Vegetated biofilters exhibit consistently better TN removal performance than non-vegetated systems. Bratieres et al. found that vegetated biofilter columns had TN removal rates as high as 70% (2008). The highest TN removal rates were associated with the plant species that produced the densest root systems, which provided the greatest surface area for uptake of nitrate and ammonium. They also found that the effect of plants increased over time, as initial plantings become established. This is attributed to increased biomass, in particular the establishment of extensive root systems. The beneficial effect of vegetation on nitrogen removal performance has subsequently been confirmed by Lucas and Greenway and Barrett et al. (2008; 2013).

4.3.1.3 Temperature

Since nitrogen removal is principally biologically driven, the season and ambient temperature can have a strong impact on nitrogen removal performance. Blecken et al. found nitrate production and leaching to be much higher at 70°F than at near-freezing temperatures (2007). This is attributed to increased microbial activity (nitrification) at higher temperatures. Field testing of seasonal variations in nitrogen removal performance for two bioretention cells in New Hampshire showed that nitrogen removal decreases in winter, but that the decline was less pronounced than that of more conventional stormwater BMPs (Roseen et al., 2009).

4.3.1.4 Media Depth / Subsoil Permeability

Nitrogen removal on bioretention cells is limited by contact time. Hunt et al. suggest a media depth of at least 0.75 m to ensure adequate contact (2012).

4.3.2 Design Variations to Improve Nitrogen Removal Performance

Published literature has indicated a number of design modifications for nitrogen removal mechanisms that are discussed in the following sections.

4.3.2.1 Use of an Internal Water Storage Layer (IWS) to Promote Denitrification

Facilitating denitrification through the creation of an anoxic layer within a bioretention cell was first suggested by Kim et al. (2003). Complete nitrogen removal requires stormwater to flow through aerobic and anaerobic environments in sequence.

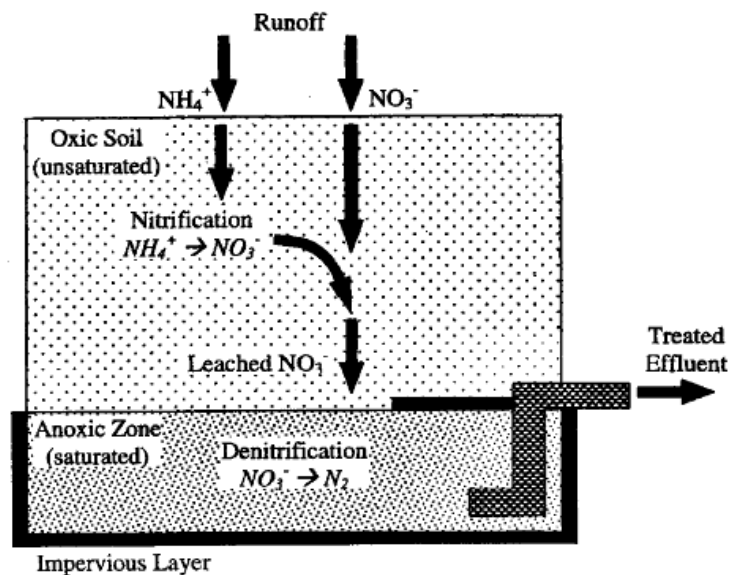


Figure 4-2. Diagram Showing Desired Nitrogen Dynamics
Source: Kim et al., 2003

Creation of an IWS has the capacity to significantly reduce nitrate and TN in outflow, but in order for it to work, the IWS needs to stay saturated long enough for anaerobic conditions to develop between storm events (several days). Bioretention cells with sandy subsoils can have exfiltration rates too high for the IWS to remain saturated for more than a few hours. Bioretention cells with subsoils containing more clay have much lower exfiltration rates, leading to prolonged saturated conditions in the IWS, which permits the development of an anaerobic zone where denitrification can take place (Brown and Hunt, 2011b; Passepport et al., 2009).

A second apparently critical factor in the success of using an IWS to reduce effluent nitrogen is in the media selection. The media selected must be as low in organic nitrogen as possible. Organic nitrogen in the IWS, whether from compost, leaf mulch, or topsoil included in the media, will partially but not fully degrade in an anaerobic environment. Some ammonification can take place in anaerobic conditions, but nitrifying bacteria require oxygen to convert ammonium to nitrite and then to nitrate. Denitrifying bacteria can convert nitrate to nitrogen gas, but cannot make use of ammonium. This results in a buildup of ammonium and dissolved organic nitrogen in the anaerobic zone, which is unavailable to denitrifying bacteria, and is flushed from the system in subsequent storm events. Use of an inorganic media, such as sand, is therefore recommended in the IWS.

The media cannot be entirely inorganic, however. Denitrifying bacteria require a carbon source to use as an electron donor. Kim et al. tested several high carbon, low nitrogen materials, and found that shredded newspaper provided the optimal mix of carbon accessibility and resistance to degradation (2003). They recommend using a mixture of sand and finely shredded newspaper in the IWS layer. The history of experiments testing this design is presented in Brown and Hunt (2011).

4.3.2.2 Use of Alternate Filter Media

Bioretention specifications across the country vary with respect to the required composition of the filter media. In addition, researchers have evaluated the performance of a variety of potential media compositions and configurations, both in the laboratory and in the field.

In the aerobic zone, nitrogen removal is promoted by the use of a medium with a high cation exchange capacity and low nitrogen content. Organic matter is needed to provide the desired cation exchange capacity, and even some anion exchange capacity, which contributes some ability to adsorb nitrate anions, but it appears to be important that the selected organic matter have a high C:N ratio in order to avoid leaching of nitrogen from the media.

Table 4-1. C:N Ratio of Commonly Used Organic Media

Medium	Typical C:N Ratio
Composted yard waste	Varies depending on inputs. grass clippings: 10-20* leaves: 60-80*
Topsoil	10-20 [#]
Shredded hardwood mulch	400 [#]
Peat	58 ⁺
Newspaper	120 [#]

*data from WVU Extension (<http://www.wvu.edu/~agexten/wastmanq/compost.htm>)

[#]data from Brady and Weil (2002)

*data from WSU Extension (http://whatcom.wsu.edu/ag/compost/fundamentals/needs_carbon_nitrogen.htm)

Pitt and Clark found significant nitrate removal only in columns that contained granular activated carbon (GAC) (2010). They note, however, that the removal of nitrate by GAC was associated with the release of phosphate.

4.3.2.3 Inoculation with Mycorrhizal Fungi

Bratieres et al. found that biofilters planted with *Melaleuca spp.*, which exhibited good nitrogen removal, were extensively colonized with root-associated arbuscular mycorrhizal fungi (2008). These fungi are known to facilitate nutrient uptake by plant roots. Inoculation of biofilters with these fungi has not yet been tested, but could potentially give a boost to plant uptake. The colonies would probably form over time naturally, but this could expedite the process.

4.3.2.4 Addition of Biochar

Biochar may have significant potential to prevent leaching of nitrate and phosphorus from bioretention cells. To date, no testing data have been published using biochar as a component in bioretention media, but such research is underway at several institutions. A recent study by Beck

et al. tested the effect of the addition of biochar to green roof planting media on nitrogen and phosphorus outflow concentrations (2011). They found that the addition of biochar to the planting medium significantly increased retention of nitrate, total nitrogen, phosphate, and total phosphorus compared to the control group.

4.4 Phosphorus Removal

Particulate phosphorus is effectively filtered by biofiltration media. Removal of dissolved phosphate, however, has been highly variable. Phosphate can react with metals, metal oxides, or organic matter, and is taken up by plants (Pitt and Clark, 2010). Phosphorus leaching can occur when media with high phosphate concentrations are used.

4.4.1 Variables That Can Impact Phosphorus Removal Performance

Phosphorus removal is dependent on the variables discussed in the following sections.

4.4.1.1 Media Phosphorus Content

The p-index of biofiltration media plays a determinative role in phosphorus removal performance. Hunt et al. found that bioretention cells constructed with soils with low p-indices effectively removed phosphorus, while cells constructed using soils with high p-indices exported phosphorus (2007). This finding has been confirmed by a number of studies.

4.4.1.2 Organic Matter

The amount and type of organic matter used in biofiltration media also has a strong impact on phosphorus removal. Compost has been shown to leach phosphorus. Hunt et al. recommend limiting the amount of organic matter used in the media mix, and choosing organic matter sources that are less liable to leach phosphorus (2012).

Shredded hardwood bark mulch has received interest as a potential organic matter source that could provide some of the benefits of organic matter, namely increased water holding capacity, while limiting the undesirable effects of organic matter, such as leaching of nutrients.

4.4.1.3 Vegetation

Vegetation plays a significant role in phosphorus removal, as demonstrated by Lucas and Greenway, who found that vegetated bioretention mesocosms were better able to retain phosphorus than unvegetated mesocosms (2008). Unfortunately, this work was done in Australia, using grasses (Swamp Foxtail Grass and Flax Lily) and two woody shrubs (Banksia and Bottlebrush) native to Australia. Recent work suggests that grasses with extensive root systems may be the most important species for nutrient processing in bioretention (Barrett et al. 2013).

4.4.1.4 Anoxic Conditions

The use of an IWS layer to improve nitrogen removal can impair phosphorus removal. Under reducing conditions, phosphate bound to iron oxides becomes more soluble and can leach from the media (Stumm and Morgan, 1996). Therefore, the bioretention system should be designed

with a deep enough upper aerobic zone to ensure that phosphate is removed from solution before infiltrating stormwater reaches the anoxic IWS layer.

4.4.1.5 pH

Pitt and Clark found that phosphorus removal was correlated with soil pH and inversely correlated with soil organic matter content (2010). Phosphorus removal would be expected to be highest at very low and very high pHs, and phosphorus is most soluble between pH 6-7, which is within the range seen in most biofilters (Brady and Weil, 2002).

4.4.2 Design Variations to Improve Phosphorus Removal

Phosphorus removal is complicated with the addition of leaching from the media and vegetation within various stormwater control measures (SCMs). Traditional bioretention relied on mechanisms to physically remove phosphorus such as sedimentation and filtration that addressed particulate phosphorus. The following design modifications are proposed based on published studies and current understanding of phosphorus removal mechanisms.

4.4.2.1 Media Depth

When phosphorus is primarily in particulate form, it can be filtered out of stormwater using a shallow media layer (Hsieh et al., 2007). However, when stormwater contains a large amount of dissolved phosphate, a deeper media layer is needed for phosphate sorption. Hunt et al. recommend designing bioretention systems with a 0.45 – 0.6 m upper aerobic zone (2012). An IWS layer can be used below this layer to enhance nitrogen removal.

4.4.2.2 Use of Media with a High Capacity to Sorb Phosphorus

The potential of a material to sorb or leach phosphorus should be carefully considered when selecting media for use in bioretention. Organic matter should be limited to 5%, and low phosphorus materials, such as shredded hardwood bark mulch, should be given preference. Look for soils with a low p-index, high concentrations of manganese, iron, and aluminum oxides (e.g., gibbsite, goethite), and clays with high anion exchange capacities (e.g., kaolinites).

4.4.2.3 Water Treatment Residuals

Recently, researchers have begun to examine the potential use of water treatment residuals (WTR) as a component of the biofiltration media to improve phosphorus removal. WTR is a by-product of drinking water purification, and is primarily composed of amorphous aluminum and iron oxides, which have a very high capacity to sorb phosphorus. Their effectiveness in improving phosphorus removal in bioretention has been demonstrated (Lucas and Greenway, 2011; O'Neill and Davis, 2012).

4.4.2.4 Addition of Biochar

Biochar may have significant potential to prevent leaching of nitrate and phosphorus from bioretention cells. To date, no testing data have been published using biochar as a component in bioretention media, but such research is underway at several institutions. In a study of the use of

biochar in green roof planting media, biochar significantly increased the retention of phosphate and total phosphorus from stormwater (Beck et al., 2011).

4.5 Long-term Considerations

4.5.1 Metals Saturation

Bioretention media may eventually become saturated with heavy metals. At loading rates typical of most urban runoff, this is estimated to become important 15-20 years after installation (Davis et al., 2003). At the higher loading rates than may be encountered in some industrial applications, this saturation point may be reached more quickly. Hatt et al. (2011) conducted a laboratory simulation of metals accumulation in bioretention media and estimate that Cu levels in the upper media layers would exceed ecological guidelines after 12-15 years, presenting a potential hazard to wildlife and the public. Studies by the USDA have shown that certain metals have the potential to phytoextract remediate metals (Chaney et al., 2004). Sun and Davis outline three options for dealing with this problem (2007).

1. The first option would be to periodically remove and replace the surface layer of the bioretention media, where the majority of the metals would be concentrated. This metals-saturated media would then need to be disposed of properly.
2. The second option would be to “incorporate a low-solubility substance (e.g. Fe or Al oxide) to sequester metals for long periods of time and to render them immobile”. Metal accumulation and potential breakthrough would still occur and at some point, possibly decades in the future. The media would have to be replaced in this situation.
3. The third option that Sun and Davis explored would be to use phytoremediation to remove metals from the bioretention media and concentrate them in the plants. Removing the metals in this manner would recharge the sorptive capacity of the media. Unfortunately, no additional research has been completed on this topic and no recommendations can be made on plant species or timeframes.

4.5.2 Potential for Clogging

Clogging is a frequent cause of failure of biofiltration devices. Particles become trapped at the surface, and to some extent deeper in the media matrix. Pitt and Clark tested several biofiltration media mixtures, and found that mixtures of rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss were the most resistant to clogging (2010). To prevent clogging, a pretreatment forebay should be used when the sediment load is high. Usually sediment will not penetrate deeply into biofiltration media and any clogging will occur at the surface of the media (top 10 cm) (Li and Davis 2008). Also, clogging is expected to be greatest near the runoff inlet. Remediation of clogged media may require the removal of the top few cm where the clogging occurs.

4.5.3 Climatic Considerations

There are several ways in which climatic factors might be expected to affect pollutant loading and removal performance. As has been discussed, nitrogen removal is a microbially-mediated process, which slows as temperatures drop in areas that experience cold winters. Variations in seasonal rainfall patterns may also impact loading patterns and removal performance. For example, much of the western United States experiences distinct “wet” and “dry” seasons. During dry seasons, pollutants build up on surfaces, resulting in a large flux of pollutants during the first large storm of the rainy season (Shaver and Ridley, 2007). BMPs should be adequately sized to capture and treat the first flush from these storms. In contrast, the Midwest and Eastern U.S. experience a much more evenly distributed rainfall pattern, with more or less consistent pollutant concentrations from one storm to another.

5.0 BMP SELECTION TOOLS

The selection of the BMPs or set of BMPs best suited to a given site is a complex process that requires consideration of a number of factors, including pollutant loads, water quality requirements, site constraints, and available funds for construction as well as ongoing monitoring and maintenance. In many cases, a treatment train approach may be used, with several BMPs (or BMP layers) constructed in series to address specific pollutant requirements and concentration limits. Several BMP decision support tools have been developed to facilitate BMP selection.

5.1 WERF SELECT Tool

SELECT is a Microsoft Excel-based planning level tool that allows users to test the effectiveness of using different BMPs to control stormwater on a site. The tool allows users to select from a variety of commonly used stormwater BMPs. Users input site data and select BMPs for treatment. The model then simulates storm events, calculating runoff volume and water quality data. The model also calculates whole life costs of the selected BMPs, including capital costs and ongoing costs for operations and maintenance. This allows users to quickly estimate the cost and effectiveness of a variety of stormwater control alternatives without necessitating sophisticated stormwater modeling.

5.2 NCHRP Project 25-25

The American Association of Highway and Transportation Officials (AASHTO) has developed a decision support tool for permeable roadway shoulders. The tool allows users to systematically assess the feasibility of using permeable shoulders on their projects. The tool consists of a Microsoft Excel-based decision matrix, which incorporates a variety of considerations that influence the suitability of permeable shoulders for a given project, such as depth to groundwater, geometric conditions, and the locations of utilities. These considerations are divided into primary and secondary importance levels, and are weighted based on their relative importance to the overall feasibility of the project. Proposed projects are then scored, with the score indicating how feasible incorporating permeable shoulders would be for the project.

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GLOSSARY OF TERMS

Ammonification	The microbially-mediated conversion of organic nitrogen to ammonium.
Complexation	A chemical process in which ions in solution bind with other dissolved substances.
Denitrification	The microbially-mediated conversion of nitrate to nitrogen gas.
Filtration	The process by which solid particles are removed from water by passing the water through a filtration medium with pores small enough to trap suspended particles, while allowing water to pass through.
Heavy metals	A loosely defined subset of elements, mainly transition metals, which can have toxic effects on organisms in the environment. This subset usually includes lead, copper, cadmium, mercury, zinc, chromium, and arsenic, among other elements.
Leaching	The process by which a metal or other chemical dissolves into rainwater or stormwater it comes into contact with.
Load	The quantity of a metal or other chemical that is discharged to a receiving water.
Microbial immobilization	The removal of nutrients and pollutants from solution through their uptake and storage within microbial biomass.
Microbial transformation	The transformation of nutrients and pollutants from one form to another through their use in microbial respiration or metabolism.
Nitrification	The microbially-mediated conversion of ammonium to nitrate.
Plant uptake	The removal of nutrients and pollutants from solution through translocation into plant tissue.
Precipitation	The chemical process by which dissolved substances come out of solution and into solid form, after which they can be removed via settling or filtration.
Sedimentation	The process by which solid particles suspended in water are removed by holding the water for a sufficient amount of time to allow suspended particles to fall out of suspension through the influence of gravity.
Sorption & ion exchange	A set of physical and chemical processes by which dissolved ions are removed from water by adhering to media they come into contact with.
Volatilization	The process by which a dissolved substance is converted to a gaseous form, which then escapes into the atmosphere.

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